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Evaluation of the iterative method for image background removal in astronomical images

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Abstract

For surveillance of space purposes, algorithms were developed to automatically detect satellite streaks in astronomical images (Ref. 2 and 3). However, the performances of the algorithms for the background removal were not tested. This technical note contains a short analysis that proves that image backgrounds are adequately removed with the algorithms described in Ref. 2. It also contains an algorithm variation that makes it more reliable. The analysis of image residues shows that the residual background is fainter than the detection sensitivity threshold and does not affect the detection performance.

Résumé

Pour des fins de surveillance de l'espace, des algorithmes ont été développés pour détecter automatiquement les traces de satellites dans les images astronomiques (Réf. 2 et 3). Cependant, les performances des algorithmes pour enlever les arrière-plans n'ont pas été vérifiées formellement. Cette note technique contient une courte analyse qui prouve que les arrière-plans des images sont enlevés adéquatement avec les algorithmes de la Réf. 2. Elle contient aussi une variation de l'algorithme qui rend ce dernier plus fiable. L'analyse des résidus de l'image montre que l'arrière-plan résiduel est plus faible que le seuil de sensibilité de la détection et qu'il est sans conséquence sur les performances de la détection.

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1. Introduction

The detection of satellite streaks in astronomical images requires a good algorithm for the removal of the image background. The classical method for background removal consists of acquiring a dark frame and by subtracting this dark frame from the next acquired image. A dark frame is an image acquired with a closed shutter. Hence, only the CCD artifacts and background are acquired. However, Ref. 1 demonstrated that this method is not accurate enough. The dark frame variations are too great to obtain a real background-free image, and the dim target detection algorithms (satellites) are not properly optimized due to insufficient background removal.

Therefore, an improved algorithm to remove the background by processing was developed in Ref. 2 along with other algorithms for streak detection (Ref. 2 and 3). However, the performance of the background removal algorithm was not verified and some doubts remained. If the background is not adequately removed; 1) a part of the relevant signal can be removed with the background or, conversely, 2) a remaining part of the background may cause an over estimation of the residual noise. Those two cases reduce the optimization of the image exploitation algorithms that follow.

This document presents a complement of information following on the previous publications (Refs. 1 to 3). It contains a short analysis that confirmed that the background was adequately removed. This eliminates the doubts that persisted. To illustrate the needs for such algorithms, Fig.1 shows examples of image before and after background removal.

It was found that some acquisition scenarios were not compatible with the algorithm previously developed in Ref. 2. This document presents a more robust method for the background removal based on local statistics rather than polynomial fit done on the image lines and columns.

This work was performed from Feb 2007 to Aug 2007 under WBE 15ee03 “Small Telescope for Surveillance of Space”.

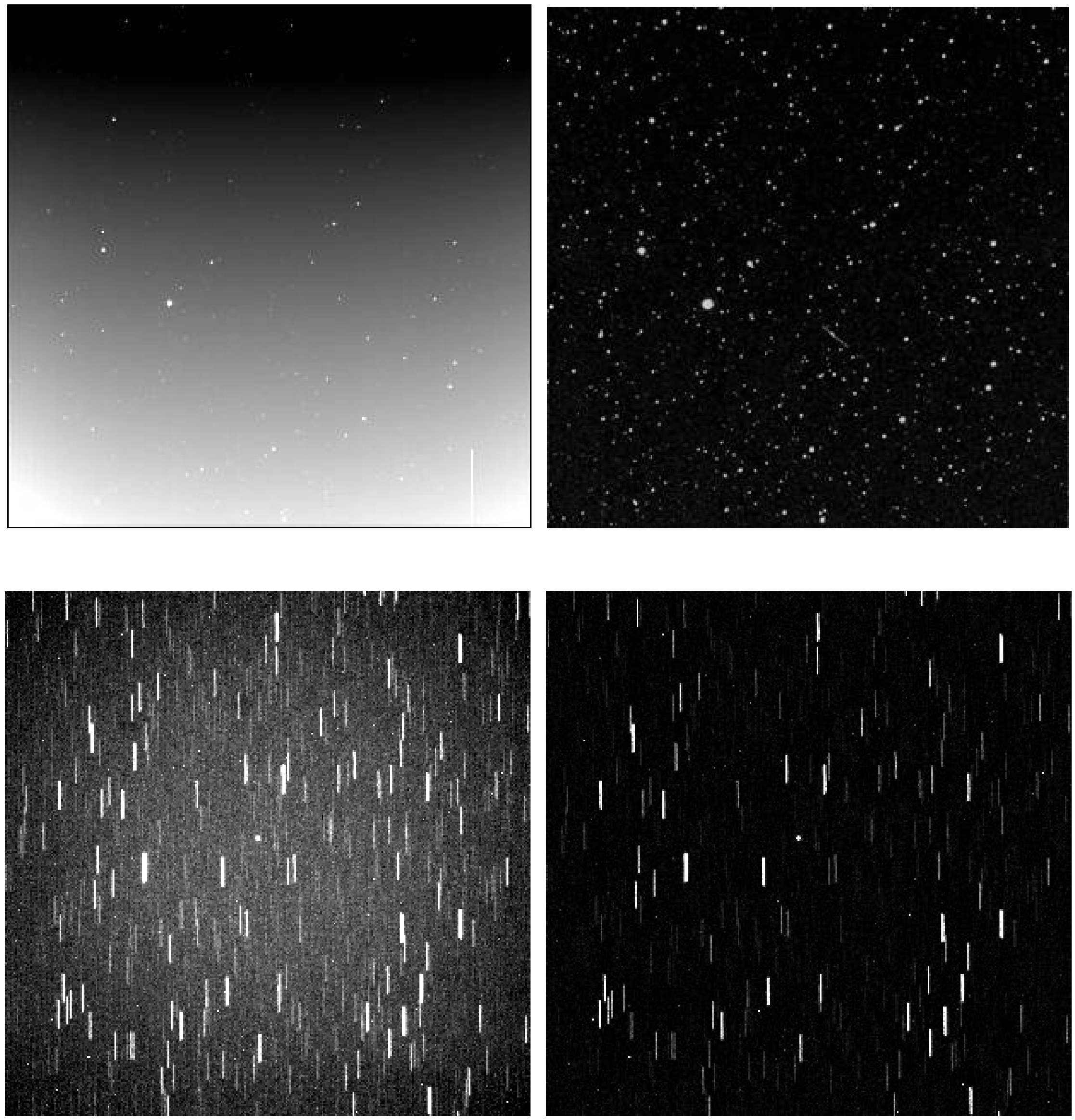

Figure 1 – Example of image acquired in sidereal and satellite tracking mode by different CCD cameras (the background patterns are not similar). The left and right sides show the original and background corrected images.

2. Signal model

The examples of Fig. 1 illustrate the need to remove the background. To develop an algorithm suitable for this purpose, a good mathematical model is required to describe the signal. Here are the guiding principles that allow separating the image into several independent components. First, the acquired image ‘I’ is the summation of an image background ‘B’ produced by the sensor, plus a signal ‘S’ produced by the significant light sources, plus an inevitable noise source ‘n’;

$$I = B + S + n$$

The particularity of the signal ‘S’ is that it is zero everywhere, excepted for few pixels where a star produce a very sharp and strong impulse. Because of this particularity, the image background can be seen between the stars. This makes easy the separation of the background and the signal.

To evaluate the image background ‘B’, it is mandatory to spot the pixels containing significant signal and ignore them in the background computation. So, exclusion zones ‘E’ are defined for the pixels where (example in Fig. 4B):

$$E = 1 \text{ when } S > 2\sigma_n \text{ and 0 elsewhere.}$$

However, it is often more useful to use the inverse of the exclusion zone, i.e., the valid noise or non-signal pixels ‘N’;

$$N = 1\text{-}E$$

This allows creating an image ‘I_b’ almost free of signal, containing only the background and noise;

$$I_b = N \; I \quad = B + n$$

By smoothing this last image, the noise is reduced and a very good estimation of the image background <B> is obtained;

$$\langle B \rangle = \text{local mean } (I_b)$$

By subtracting this background estimation from the signal-free image I_b, there remains only a residue ‘r’ which is composed of the residual background ‘b’ and noise ‘n’.

$$r = I_b - \langle B \rangle = b + n$$

where

$$b = B - \langle B \rangle$$

The residual background is the difference between the real background and its estimation. If the background is correctly estimated, the background residue almost vanishes ($b \approx 0$). Then, the real signal can be separated and the background-free image can be produced with;

$$S + n \approx I - \langle B \rangle$$

Ideally, the background residue 'b' should be zero or, at least, smaller than the noise. This was not verified in the previous studies (Refs. 2 and 3) - that is the goal of the current publication.

3. Background removal algorithms based on local statistics

The issue with the above described signal model is that both background and signal must be known a priori to be able to accurately isolate one of then. Also, the exclusion zones remain unknown until the background and signal are separated. However, by supposing that the background is relatively smooth and the signal very sharp, it is possible to make estimations. Using an iterative process, the estimations can be refined until a very good knowledge of signal and background is obtained. The estimation tolerance error is reduced at each step. The iterations stop when there is no more improvement or the residual error is less than the noise level. This iterative process is illustrated in Fig. 2.

Two equivalent methods were developed. The differences are only in the background sampling and estimation method. The method described in Ref. 2 uses polynomial fit while the method described in the present document uses local statistics (local mean and standard deviation). Because the signal is almost zero everywhere, a smoothed image is already a good but imperfect background estimation ($\langle B_1 \rangle$), and the signal above this background is also a first estimation of the signal (S_1);

$$\langle B_1 \rangle = \text{local mean } (I_0)$$

Remember that the exclusion zones are not determined yet and, at certain locations, the background is overestimated because of the presence of signal. To obtain a better background estimation, the signal must be attenuated before again estimating the background. This is obtained by clipping the image with;

$$I_i = \text{minimum } (I_{i-1} , \langle B_i \rangle + 2\sigma_n)$$

Hence, in the next image, the levels of the pixels affected by signal are replaced by the local mean while the background pixels are preserved. At each iteration, the signal is clipped and the result converges toward the background. After a few iterations, the background is well estimated. This iterative process is illustrated in Fig. 2. Figure 3 illustrates how a very bright star is systematically clipped at each iteration.

This iterative approach was also used in Ref. 2 but with a different background estimator. The background is obtained by first fitting a polynomial over the image columns and then over the image lines. This method processes adequately both images of Fig. 1. The issues occur when the vertical streaks are twice the length of those illustrated in Fig.1 (in satellite tracking mode). It occurred that the initial guesses were too far from the solution, the contribution of the streak was too important in the polynomial fit, and that the method was unable to converge towards a solution.

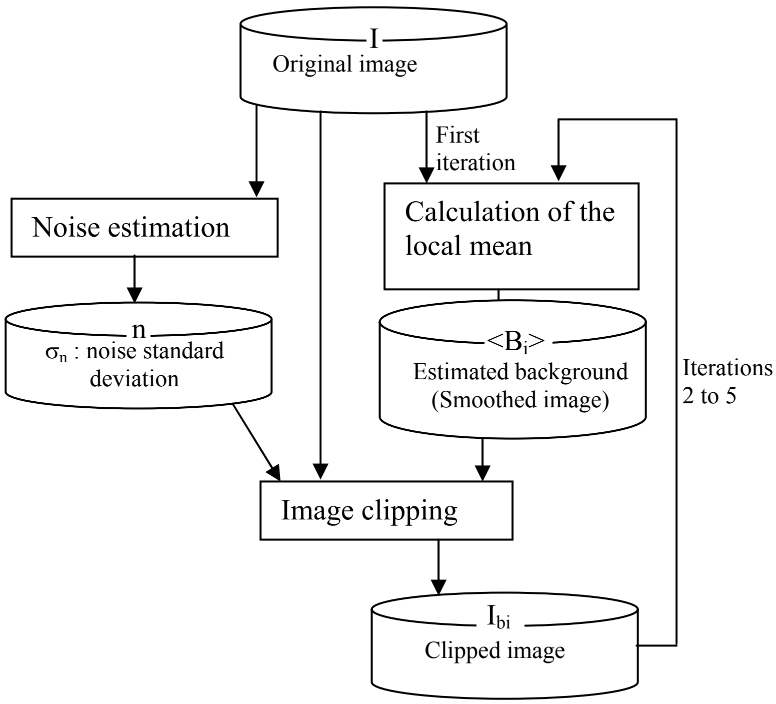

Figure 2 – Estimation of the image background with an iterative image smoothing and clipping process. The last clipped image is the final background estimation.

The use of local means is not sensitive to streak length and orientation. It uses local statistics calculated over local windows several times larger than the optical PSF (point spread function). Typically, windows with 5 and 10 times the PSF width are used. Hence, for a 3 pixel width PSF, the local window sizes are 15x15 and 31x 31 pixels. Figure 3 indicates how the local mean calculation evolved with several iterations.

The best convergence was achieved with an alternation of window sizes. With a large window, the local mean is less sensitive to very bright stars. But, when such a star is encountered, the signal bump is very large. Smaller windows produce smaller bumps but with higher amplitude. The best results are obtained when both window sizes are used and combined. The combination is achieved by calculating the minimum of both functions. This produces a sharp filter insensitive to very bright stars. A winning combination was the alternate use of 31x31 and 15x15 pixel windows (for a PSF of 3 pixels). This assures a quick convergence and preserves sharpness.

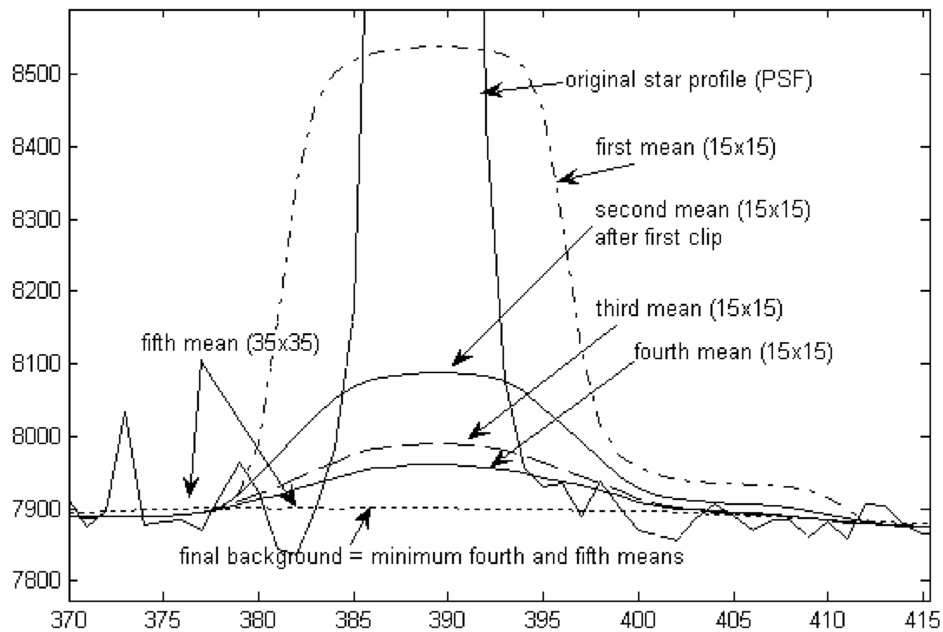

Figure 3 – Iterative background estimation with an image more precisely clipped at each iteration.

The exact size of the windows and the number of iteration are not critical values. The method always converges toward a clean result. However, this method is very long to compute and requires a clever algorithm implementation. The use of partial summations and reusing intermediate results were necessary to obtain good code performance.

The use of local windows is sensitive to border effects. To counter this effect, local statistics were evaluated using variable-size local windows. A narrow window is used close to the image border. The window width increases when the window moves away from the image border until it is far enough to have the full size. This produces less accurate local statistics on the image border but avoids introducing any windowing artifacts.

Figure 4 shows the image components that are extracted with these algorithms. The noise is not stationary and its local standard deviation is calculated over the entire image, (not shown). The first presented image is the fifth background ($<B_5>$) estimated with the process of Fig. 2. The image below (the background-free image), is simply the result of the original image less that background ($S = I_0 - <B_5>$). The exclusion zones indicate the pixels that contain signal. These pixels will be systematically ignored in the following noise analysis (Chap. 4). Finally, the shown residue 'r' (composed of the residual background plus the noise) is the remaining signal between the exclusion zones.

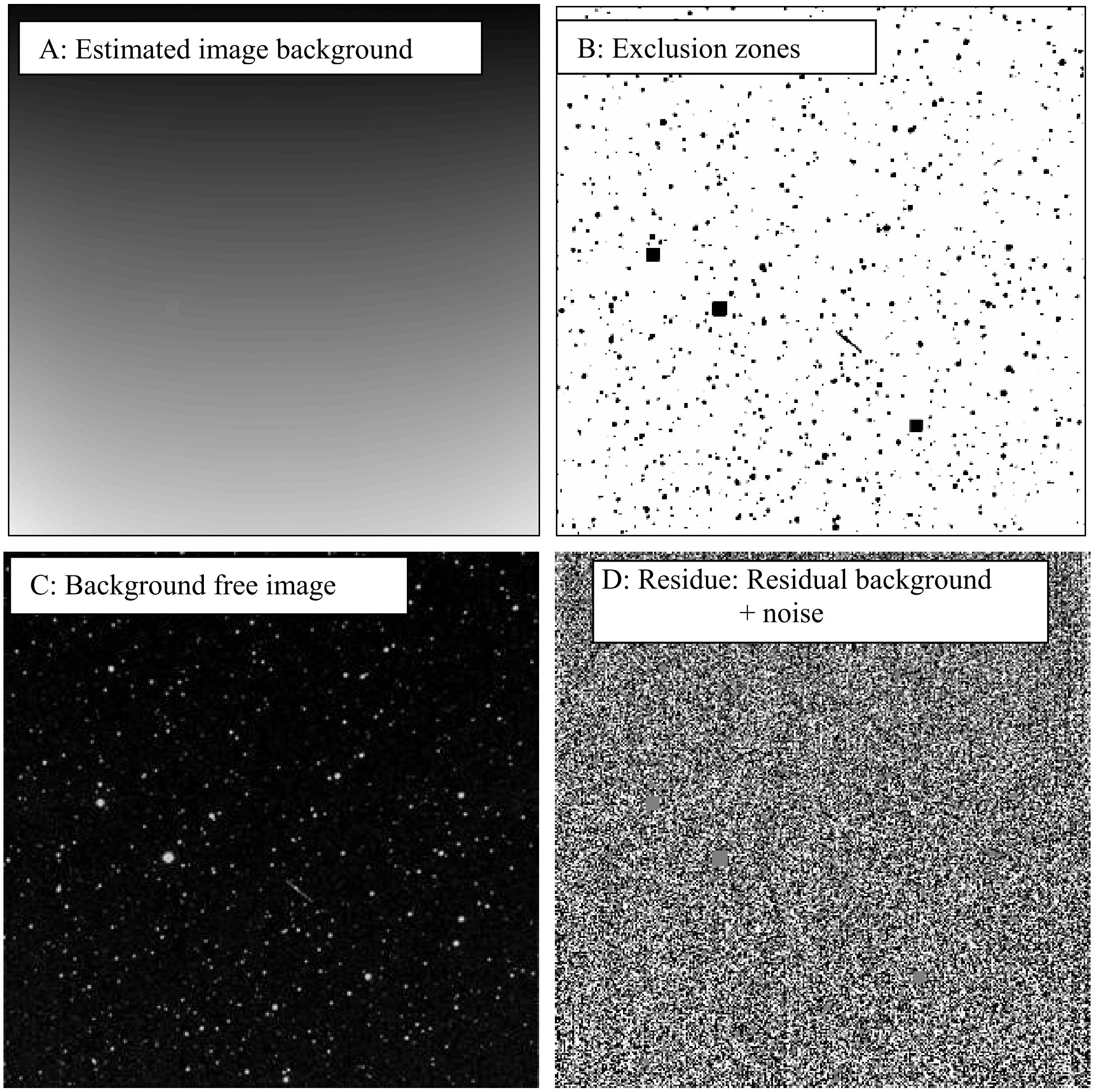

Figure 4 - Separated image components.

Dynamic ranges are different for each image; background range is 6000 counts, the range of the background-free image is 300 counts above the noise level and the noise image range is from $-\sigma_n$ to $+\sigma_n$, i.e., around 50 counts (in this example, $\sigma_n = 27$). The exclusion-zone image is a binary image.

4. Analysis of the image residue

The analysis of the residue properties can indicate if the background was correctly estimated. Considering that the noise mean is zero (if, after having subtracted the background, the negative values are preserved), a residue measurement equal to zero suggests that there is no residual background. There should be no bias in the residue measurement, at least not bigger than statistical errors on the noise mean estimation.

During the calculation of these residue properties, special attention was paid to excluding the pixels containing signal, to avoid the corruption of the noise by signal (instead of the usual corruption of the signal by noise). Special attention was also paid to border effects by using variable window size close to the image border. The combination of these two constraints forces the calculation of local statistics over variable window sizes with variable pixel contents. This makes the program code more complex and reduces performance (longer computation time). However, a clever computation code can perform almost as well as code that uses a constant window size and content.

The exclusion zones are defined to indicate the pixels containing signal. They are obtained using the background-free image I_b, by calculating the local means and selecting pixels where this local mean is still above the noise standard deviation (σ_n). These high mean values indicate the presence of signal (stars or streaks). Using the means allows the creation of exclusion zones slightly larger than the star bright pixels only. The exact applied recipe is slightly more complicated because it also takes into account that the very bright stars have very larger zones of influence. So the implemented rule is:

$$E(ij) = 1 \quad \text{if } \mu_{(5x5)}(i,j) > \sigma_n \text{ or } \mu_{(25x25)}(i,j) > 10\sigma_n$$

$$N(i,j) = 1\text{-}E(i,j)$$

where the exclusion ‘E’ of the pixel (i,j) is a combination of tests that use the local mean ‘μ’ evaluated over a (5x5) of (25x25) pixel window. The window size is not critical; the idea is to use a small window to detect all narrow stars and a larger window to indicate the zones of influence of very bright stars. This rule was used to calculate the image of exclusion zones of Fig. 4.

The exclusion ‘E’ is not suitable for the estimation of the residue means. The notion of valid noise pixel or null signal ‘N’ is more useful for the calculation of the local statistics because it can be used as a weighting function. These valid noise pixels are shown in the image residue of Fig.4 where the background-free image is multiplied by the N function. This removes all traces of signal.

Noise profiles were extracted from residue images obtained by both methods of background removal (polynomial fits and local means). Figure 5 shows such a profile. With both methods, the residual noise seems to have the expected properties. If there

is a background residue, it is considerably fainter than the noise standard deviation. Therefore, the background was adequately removed by both methods.

The noise distribution was also analyzed for both image of Fig. 1 and the distributions are displayed in Figs. 6 and 7. Figure 6 indicates that the noise is not uniform with the Valcartier SofS/CD CCD camera. Cooling down the CCD temperature (when possible) reduces the noise standard deviation but this camera has always produced this characteristic of non-stationary noise. Such noise dispersion is not observed with the Ottawa SofS/CD CCD camera. These distributions show that the residual noise is really of Gaussian type centered on the zero value (after background suppression).

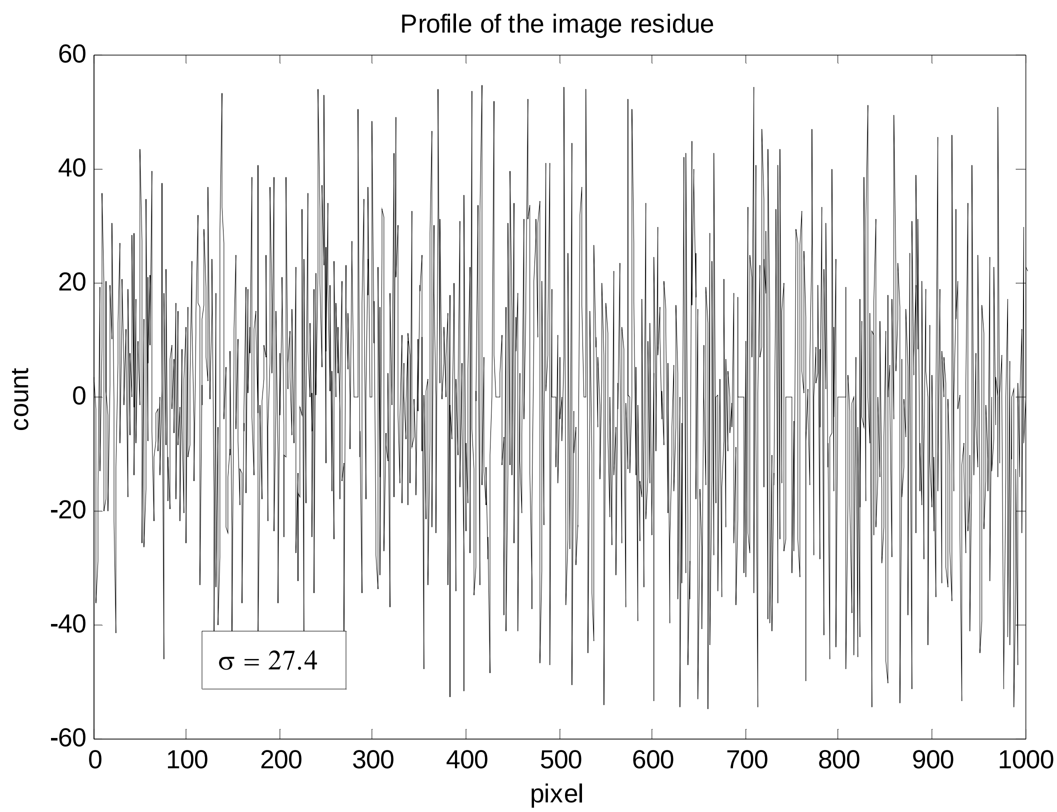

Figure 5 – Profile of the residue extracted from the image of Fig. 4.

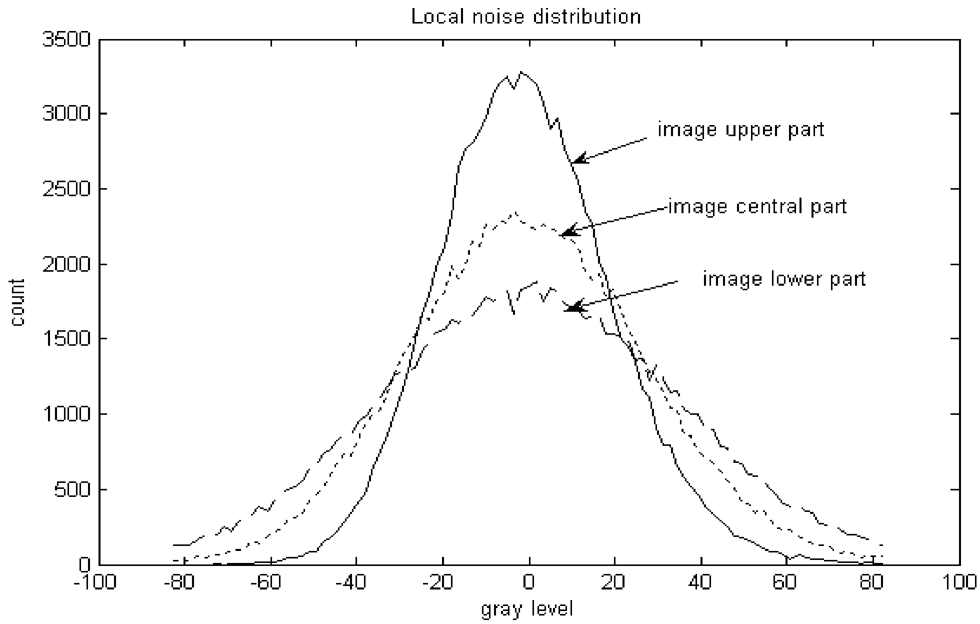

Figure 6- Distributions of the residual noise of the image acquired in sidereal mode (in Fig. 1). Distributions are measured at the top, middle and bottom of the image. This image was acquired by the DRDC-Valcartier SofS/CD CCD camera. The noise standard deviation is more important in the bottom of the image.

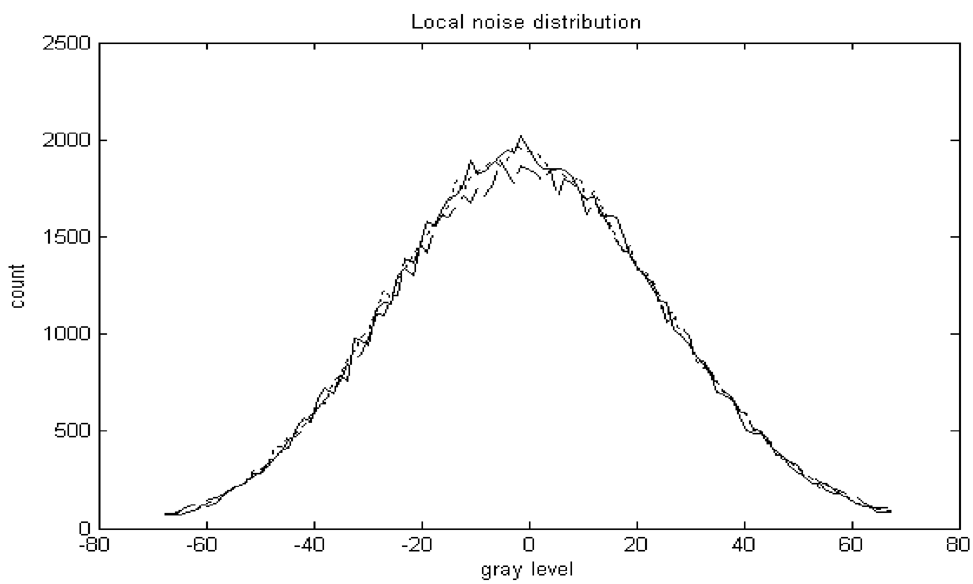

Figure 7- Distributions of the residual noise of the image acquired in satellite tracking mode (in Fig. 1). Dfistributions are measured at the top, middle and bottom of the image. This image was acquired by the DRDC-Ottawa SofS/CD CCD camera. The noise standard deviation is uniform over the entire image.

However, Ref. 3 demonstrated that the detection algorithms are very sensitive. They can detect a satellite streak as faint as SNR=0.2 and completely without false alarms with a SNR=0.5. Therefore, a background residue of the same amplitude could be the cause of false alarms. The image residue (noise and residual background) must be deeply analyzed. The possible remaining bias must be measured. Ideally, it should be lower in intensity (count) than a possible streak. Therefore, the residual background should be lower than $\sigma_n/2$ (equivalent to SNR=0.5) or even better $\sigma_n/5$. Figure 5 does not allow seeing such a bias in the noise envelope. However, it is possible to average the signal over an area equivalent to a satellite streak (200 to 400 pixels) and measure the residue average value.

The local residue average $\mu_r\,(i,j)$ is calculated using only the noise-only pixels (i.e. when N(i,j)=1) with the following equation;

$$\mu_r\,(i,j) = \frac{\sum_{i-w_i}^{i+w_j} \sum_{j-w_j}^{j+w_j} N(i,j)\; r(i,j)}{\sum_{i-w_i}^{i+w_i} \sum_{j-w_j}^{j+w_j} N(i,j)}$$

where r(i,j) is the residual noise, (i,j) the pixel coordinates and w_i and w_j the variable half window height and width. The window size parameters w_i and w_j are adjusted with the proximity of the image borders.

Both methods of background removal (the polynomial or local-mean method) were applied on the image. No significant differences were noted between the two methods. The examples of Fig. 4 are valid for both methods. The local-mean noise images and profiles are shown in Figs. 8 and 9. They indicate that the local-mean method seems slightly more efficient. The polynomial background-removal method leaves a residue with amplitude about +/- 2 counts (about $\sigma_n/10$). The local-mean background-removal method leaves a similar residue but with less local variations. Measured on the whole image, the residual bias is estimated to -0.5 count and it is almost constant everywhere. By comparing Fig. 9 with Fig. 5, one can see that the goal of obtaining a background residue lesser than $\sigma_n/5$ is achieved with both methods.

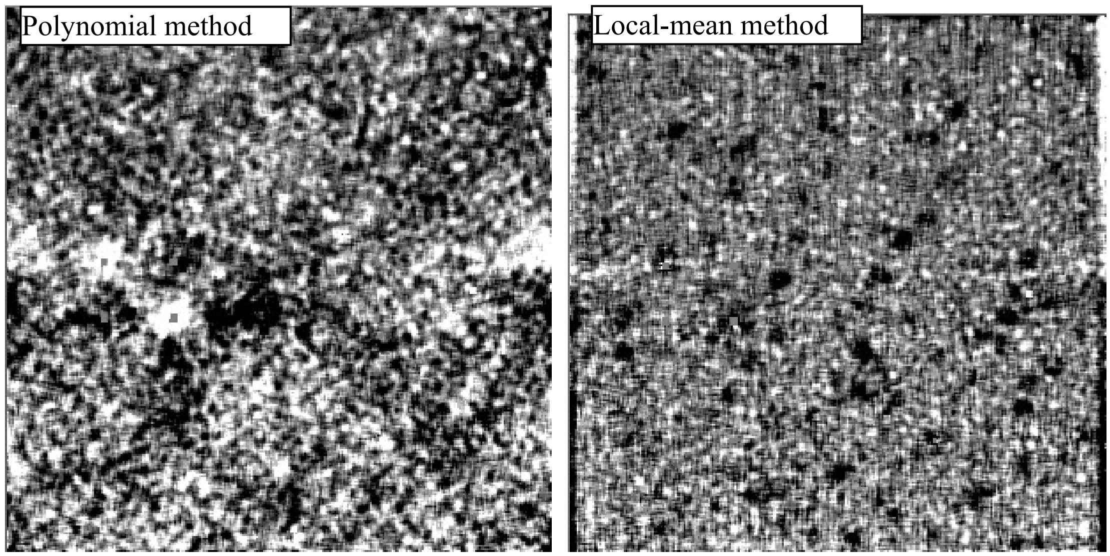

Figure 8- Local mean of the noise calculated on the residual noise obtained by both methods. The image background is removed with the polynomial method in the left image and by the local mean in the right image.

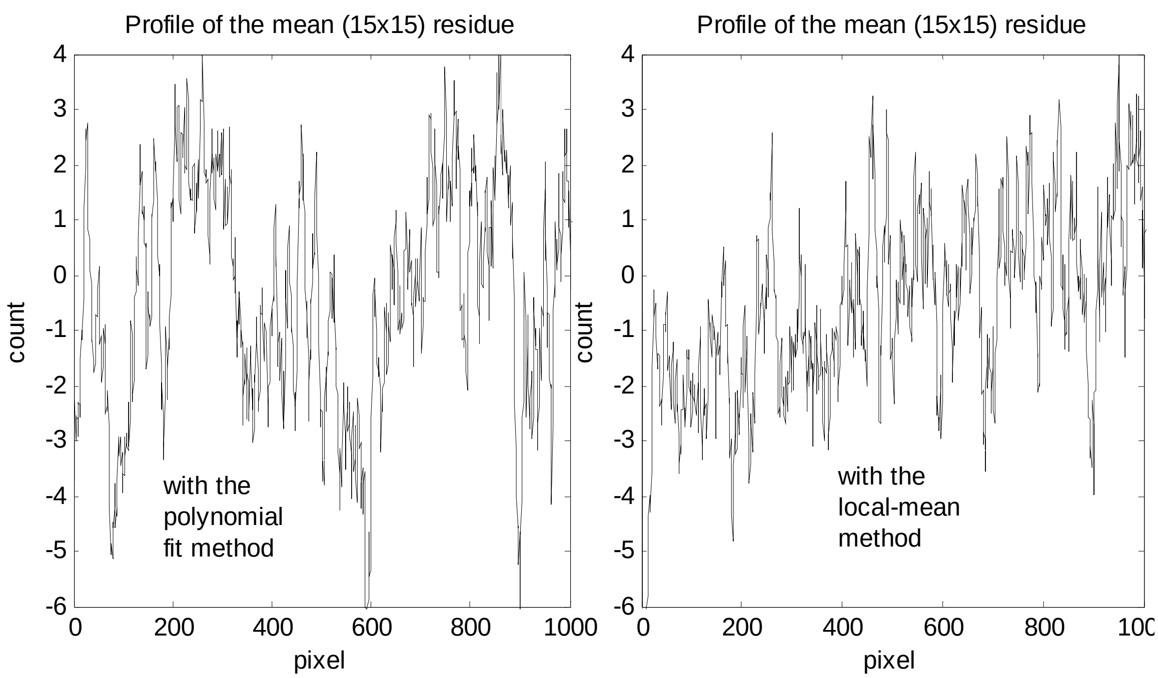

Figure 9- Noise-mean profiles extracted from images of Fig. 8.

5. Summary

In summary, this technical note eliminates the doubt regarding the efficiency of the background removal method published in Ref. 2. The background was adequately removed. Furthermore, the other method presented in this paper, based on local statistics, is slightly better than the Ref. 2 method based on polynomial fit. For both methods, the background residue was measured and it is lower than the faintest detectable satellite streak. Note that the local mean method is not sensitive to the streak direction and length, while the method based on polynomial fit can fail under certain circumstances.

The background residue is a parameter that limits the streak detection sensitivity and one can postulate that, with fainter residue, fainter satellite could be detected. It would be possible to merge the two background estimation methods (with a weighting or voting function) and add a feedback to further correct the background and get a 'more ideal' residual noise (if an ideal noise exists) but the improvement would not be significant. Also, Ref. 3 demonstrated this is not needed because it is not possible to extract useful information (accurate center of intensity, i.e., streak central position) from such faint streaks. Therefore, it is not believed that more studies are required regarding background removal, at least in that context.

6. References:

1. Lelievre M., Lévesque M. P., 2007. Evaluation of the accuracy of the dark frame subtraction method in CCD images processing. DRDC Valcartier TN 2007-343. Defence R&D Canada – Valcartier.

2. Lévesque M. P., Buteau S., 2005. Image Processing Technique for Automatic Detection of Satellite Streaks. DRDC Valcartier 2005 TR-386. Defence R&D Canada – Valcartier.

3. Lévesque M. P., Lelievre M., 2006. Improvements of satellite-streak detection by the use of false alarm rejection algorithms. DRDC Valcartier TR 2006-587. Defence R&D Canada – Valcartier.

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